Plasma Lines in the Auroral *E* Layer

VINCENT B. WICKWAR

SRI International, Menlo Park, California 94025

The first successful measurements of plasma lines in the auroral *E* layer were made in January 1976 using the Chatanika incoherent scatter radar. Although they are considerably weaker than the signal from the ion component, the plasma line signals are readily detectable. Typical signal-to-noise ratios were about 4%. In this series of experiments, plasma lines were observed in the interval between 3.8 and 6.0 MHz, which corresponds to phase energies between 0.55 and 1.4 eV. They were found between 98 and 134 km; the derived plasma wave intensities varied between 0.06 and 1.0 eV, and the enhancements between 4 and 30 times the thermal level. There was a marked altitude dependence: the weakest waves were at the lowest altitudes, and the strongest were just below the maximum altitudes. There was no discernible frequency dependence at the lowest altitudes, but at the highest altitudes the lower-frequency plasma waves were stronger. These variations are probably related to the altitude variations of the suprathermal electron spectrum and of the electron temperature.

INTRODUCTION

Since 1971 the SRI International incoherent scatter radar at Chatanika, Alaska, has been used to measure the ion component of the backscatter signal. These observations have led to improved descriptions and understanding of phenomena in the atmosphere, ionosphere, and magnetosphere in the auroral region. In this paper we announce the first observations of the electronic, or plasma line, component of the signal from the auroral *E* region.

The steady state energy (or intensity or temperature) in these waves, as given by linearized plasma theory [*Perkins and Salpeter*, 1965; *Yngvesson and Perkins*, 1968], is related to the ratio of the excitation to damping rates. There is a background energy, equal to the energy of the thermal electrons, that is due to the electron thermal motion. It has been measured in the *F* region at Arecibo [*Wickwar and Carlson*, 1977]. However, most importantly, this energy is considerably enhanced when there is a suprathermal tail to the electron distribution function which increases the excitation rate by a factor greater than that by which it increases the damping rate of the plasma waves. Enhancements have been measured at *F* region altitudes and occasionally as low as 125 km when the suprathermal tail consists of photoelectrons created by the solar EUV [*Yngvesson and Perkins*, 1968; *Fremouw et al.*, 1969; *Cicerone and Bowhill*, 1971; *Wickwar*, 1971; *Vidal-Madjar et al.*, 1975]. Enhancements have also been measured at *F* region altitudes when the suprathermal tail consists of photoelectrons from the conjugate ionosphere [*Yngvesson and Perkins*, 1968; *Evans and Gastman*, 1970; *Wickwar*, 1971] and when the suprathermal tail consists of electrons energized by wave-particle mechanisms from the exceedingly energetic electrostatic plasma waves generated during ionospheric modification experiments.

The observations reported here extend past these previous plasma line results in three ways. First, the suprathermal electrons are produced by energetic auroral electrons either through collision processes [*Rees and Jones*, 1973; *Banks et al.*, 1974] or perhaps through collisionless processes [*Papadopoulos and Coffey*, 1974; *Matthews et al.*, 1976]. Even if collision processes do dominate, the spectra may be modified by collisionless processes such as are described by *Bloomberg* [1975] for the *F* region.

Second, the plasma waves than can be measured at Chatanika have phase velocities such that they exchange energy with electrons having very low energies: 0.5 eV to about 3 eV. Thus Chatanika plasma line measurements could eventually be used to learn about the low-energy electrons in this poorly known part of the electron spectrum. At these low energies, there exists the possibility of a considerable spectral structure because of the cross sections for the N_2 vibrational levels. Yet existing theoretical calculations rarely extend down to these low energies. In addition, it is an exceedingly difficult energy region in which to make measurements. I am aware of only one set of rocket measurements [*Sharp and Hays*, 1974] that extend down to as low an energy in the auroral region.

Third, the altitude region where the plasma lines are measured at Chatanika extends downward below 125 km. At low enough altitudes, electron-neutral collisions may have to be included in the plasma line theory.

Since little is known experimentally or theoretically about suprathermal electrons in the auroral region and since such knowledge can extend our understanding of wave-particle interactions and electron-neutral interactions, the Chatanika plasma line measurements can provide a valuable and unique contribution.

EXPERIMENT AND ANALYSIS

The Chatanika radar [*Leadabrand et al.*, 1972] is sensitive to electrostatic plasma waves of wavelength 11.4 cm along the line of sight of the radar. The frequency of these waves is offset from the transmitter frequency by approximately 5% more than the local plasma frequency [*Yngvesson and Perkins*, 1968]. Waves going away from the radar have a negative offset frequency, and those approaching it a positive offset frequency.

In 1975 the radar receiving system and the observation software were modified [*Petriceks*, 1976; *Dawson*, 1976] so that plasma lines with positive or negative offsets of up to 15 MHz could be observed and digitally sampled. There are three plasma line filters 100 kHz wide separated by 200 kHz; each filter is sampled once every 40 μs.

The radar observations were made with a sequence of two

Paper number 8A0604.
0148-0227/78/118A-0604$01.00

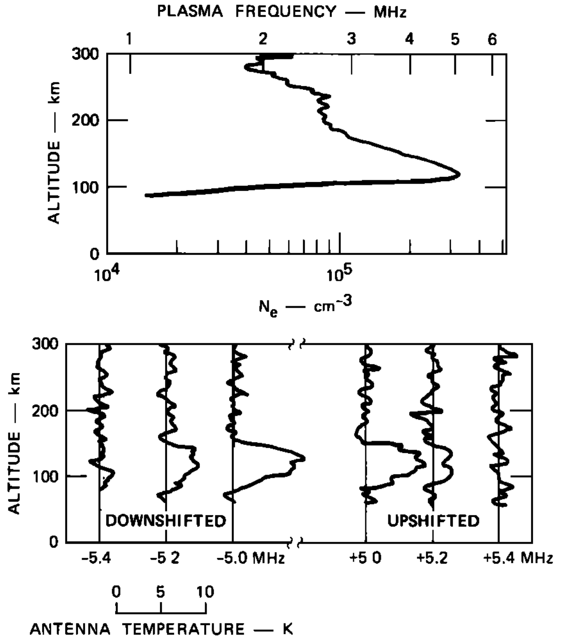

Fig. 1. The auroral E layer and both upshifted and downshifted plasma lines at Chatanika on January 20, 1976, between 1229 and 1237 UT. The plasma lines at 5.0 and 5.2 MHz are centered at 122 and 119 km, respectively. The plasma lines at −5.0 and −5.2 MHz are centered at 122 and 118 km, respectively.

pulses: the first, a 67-μs pulse to obtain the E region electron density profile from the ion component; the second, a 320-μs pulse to obtain the plasma line data (Figure 1). (Although it is not relevant to this experiment, the longer pulse could also be used to obtain ion velocities and electron and ion temperatures from the ion component in the F region.) The data from both pulses were integrated for 2–10 s and then written on tape for later processing. When requested, the computer could switch plasma line channels at each tape-write so as to change from upshifted plasma lines to downshifted lines or vice versa.

To minimize the effects of damping by thermal electrons [*Yngvesson and Perkins*, 1968], the measurements were made with the radar pointed along the magnetic field line. For the same reason the plasma line filters were tuned close to (although below) the E region critical frequency.

After the observations the data from both components were averaged for times from 1 to 10 min. The densities were analyzed in the usual fashion: the noise level was found and subtracted; the resultant powers were multiplied by range squared and were scaled according to the calibration signal. The calibration factor is routinely found by comparison of daytime F region peak densities to ionosonde measurements from Sheep Creek, approximately 50 km away. During the plasma line experiments this calibration factor was confirmed by the plasma line data shown in Figure 2. In principle, the densities need to be corrected for Debye length effects and for the temperature ratio if it is not unity. However, we are most interested in densities near the peak of the E layer, where, in practice, the Debye length correction is negligible and where our experience with E region temperatures indicates that the temperature ratio is usually close to unity.

The plasma lines were analyzed in a similar fashion: the noise level was found and subtracted, the receiver recovery signal was subtracted, and the resultant signal was scaled according to the calibration signal. The final signal strengths are given in terms of the equivalent antenna temperature.

Figure 1 shows an example of the electron densities and of both upshifted and downshifted plasma lines. The location of the plasma line filters in this example is such that plasma lines are seen at ±5.0 and ±5.2 MHz but not at ±5.4 MHz. The integration time for the plasma lines is half that for the electron density because both offsets were observed.

The altitude resolution for the density data is given by $c\tau^I/2$, where c is the speed of light and τ^I is the radar pulse length. For the 67-μs pulse it is 10 km.

The altitude resolution for the plasma line data is more complicated to find. Again, it is given by the extent of the altitude region from which the signal arises, but for our long pulse length it is determined by the filter bandwidth B^P and the altitude gradient of the plasma line frequency, $d\nu_P/dh$. The altitude resolution is $B^P/(d\nu_P/dh)$. In this example the resolution is about km, which is in agreement with the altitudes found for the pairs of upshifted and downshifted plasma lines. The long pulse length, while not adversely affecting the altitude resolution, has the advantage of providing several independent samples of the plasma line intensity.

If the plasma line intensity spectrum were flat in the vicinity of each measurement, the signal-to-noise ratio in that region would be independent of filter bandwidth [*Yngvesson and Perkins*, 1968]. Had we used a narrower filter, the signal and the noise would have been reduced by the same proportion.

The shape of the plasma line signal is approximately a trapezoid, originating from the convolution of a rectangle of length $c\tau^P/2$ with another rectangle of length $B^P/(d\nu/dh)$ and height proportional to the plasma wave intensity. In fact, the radar pulse length is often long in comparison with the E layer thickness. The signal should therefore result from the convolution with two rectangles: one on the bottomside and one on the topside. However, it can be deduced from Figure 1 that only the topside plasma line is detectable in the signal. The bottomside line is weaker because of its smaller base and lower intensity (see next section).

To continue the analysis of the data to obtain plasma wave intensities, we follow the procedure of *Yngvesson and Perkins* [1968]. The intensity, expressed as the plasma wave temperature, is obtained by combining the radar equations for the ion and plasma line components. The result is

$$T_P = T_e \frac{c\tau^I}{\delta r} \frac{1}{\alpha^2(1+\alpha^2)(1+\alpha^2+T_r)} \frac{T_A{}^P}{T_A{}^I} \frac{B^P}{B^I} \frac{G(0)}{G(\nu_P)} \quad (1)$$

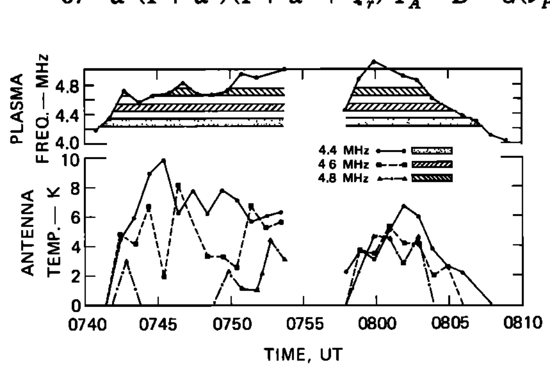

Fig. 2. Comparison of the magnitude of the auroral E layer and the existence of plasma lines at three frequencies on January 18, 1976. As the critical frequency of the layer passes through the frequencies to which the plasma line filters are tuned, the plasma lines appear and disappear. During these observations the plasma lines occur between 110 and 130 km.

where the superscripts I and P refer to the ion and plasma line components and

- B receiver bandwidth;
- T_A antenna temperature;
- $G(\nu_P)$ backscatter gain of the radar for a pulse transmitted at zero offset and signal received at an offset of ν_P;
- T_r electron-to-ion temperature ratio;
- $\alpha^2 = (4\pi D/\lambda)^2 \propto T_e$, where D is the Debye length and λ is the radar wavelength;
- δr range increment for plasma line signal, equal to $B^P/(d\nu_P/dr)$.

While the electron and ion temperatures can, in principle, be measured using a third pulse (actually three 60-μs pulses within 400 μs [*Rino et al.*, 1974]), the loss of plasma line samples and added complications did not warrant its use in this first series of plasma line experiments. Instead, the temperatures from the Cira (1972) mean model atmosphere have been used in the calculations. We also need to know how the backscatter gain of the radar varies with frequency. These data have been analyzed on the assumption that the gain is constant. This assumption appears reasonable according to recent measurements of the gain (J. Kelly, private communication, 1977), which show it to be 10% greater at -10 MHz than at $+10$ MHz.

OBSERVATIONS AND DISCUSSION

The first observations with the new plasma line receiver system were made in January 1976. Data have been reduced from those periods when the E layer critical frequency was close to or greater than the frequencies to which the plasma line filters were set.

Bumps of the expected shape for plasma lines are found in these data. These bumps are identified unambiguously as plasma lines through their interrelated altitude and time dependence. They occur at the expected altitude when the electron density in the topside E layer is converted to plasma line frequency. They vary in altitude as the altitude of the appropriate plasma line frequencies changes in response to changes in the auroral E layer. Signals were found at the same altitude for simultaneous observations at the same upshifted and downshifted frequencies. As is seen in Figure 2, the signals appeared and disappeared as the layer grew and decayed through the observed frequencies.

In this series of observations, plasma lines were found under almost all circumstances when the filters were at an appropriate location with respect to the peak size of the E layer. These plasma lines were in the interval between 3.8 and 6.0 MHz, which corresponds to phase energies between 0.55 and 1.4 eV. They were found between 98 and 134 km; at the low altitudes they were so weak that detection became difficult; at the high altitudes they were very strong, as is shown in Figure 1.

The data have been examined for a frequency dependence of the plasma wave intensity. For the upshifted plasma lines the results depend upon altitude. Above 118 km, as is shown in Figure 3, the lower-frequency waves are the more intense for the limited portion of the spectrum observed. At lower altitudes it is not clear whether there is a frequency dependence. However, as is apparent in Figure 1, an intensity difference appears to exist between the downshifted and upshifted plasma waves: the former appear to be 30% more intense than the latter. If anything, we would expect the intensities to be equalized because of collisions. While this result could be significant, confirmation will have to await the next series of measurements, which will include a backscatter gain calibration.

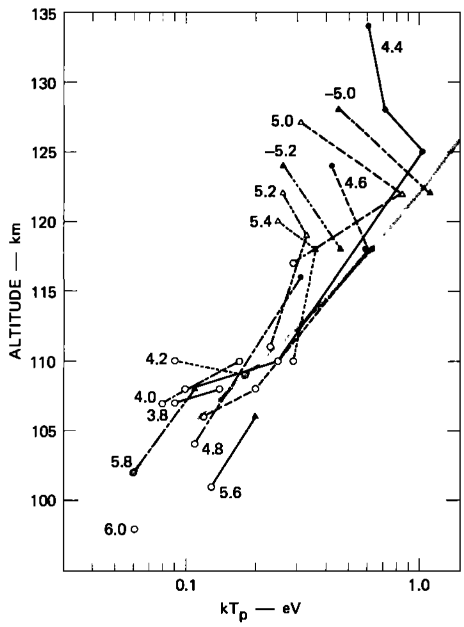

Fig. 3. Variation in altitude and plasma wave intensity of a composite of the plasma line observations. All detected plasma lines with an integration time exceeding 4 min are included. The data from January 14, 1976, are given by open circles; those from January 18, 1976, by solid circles; and those from January 20, 1976, by open and solid triangles. The plasma waves are upshifted except those denoted by solid triangles. Points for the same frequency (absolute value) are connected, and the frequency is given in megahertz. The shaded reference line is inversely proportional to the neutral number density. The altitude uncertainty is ±2 km. The intensity uncertainty is between 25 and 50%.

While the plasma wave intensity does not vary much with observed frequency, it does vary greatly with altitude (Figure 3). A plot of the enhancement ratio is very similar. All frequencies have been included in this figure, as have all the data points from integrations exceeding 4 min. For reference purposes a curve proportional to the inverse of the neutral number density from the Cira (1972) mean model atmosphere is also given. The lowest detected plasma lines, at about 100 km, are enhanced only 4 times above the thermal level, to about 0.06 eV. For each frequency the enhancement increases strongly with altitude. Between 118 and 125 km, where the enhancements are maximum, they are 15–30 times the thermal level, or at an intensity of 0.3–1.1 eV.

This basic altitude dependence (even the decrease at the highest altitudes) is very real. The major systematic uncertainty in this part of the data reduction is the use of model temperatures, but kT_P is comparatively insensitive to them. For instance, if the electron temperature were twice as large, kT_P would decrease by one third. If the ion temperature were twice as large, kT_P would increase by one third. If they were both twice as large, there would be no change. From our temperature measurements on other occasions a factor of 2 increase for either temperature is a reasonable upper bound near 135 km. However, the increase would be considerably less near 110 km. Therefore the deduced wave intensity above 120 km in Figure 3 is perhaps even greater than is shown.

These plasma line data can be used to learn about E region aeronomy with a method analogous to that used by *Carlson et al.* [1977] in the F region. By combining the data, as in Figure 3, and considering the linear plasma wave theory or model of *Yngvesson and Perkins* [1968] the variation of kT_P with altitude would enable us to examine the various terms in the enhancement equation. These terms involve the one-dimensional velocity distribution of the suprathermal electrons, f_P, the thermal electrons, and the electron-ion collisions. Because of the small enhancements, f_P can be found at the lowest altitudes. Its altitude variation and perhaps that of the neutral density can also be found. The large enhancements may additionally yield the logarithmic derivative of f_P and hence the suprathermal electron flux. Initial calculations show that the decrease in intensity at the higher altitudes may be due to elevated electron temperatures that cause the thermal damping term to become significant. It would additionally become apparent whether electron-neutral collisions need to be included in the plasma wave enhancement theory. We are considering these questions elsewhere.

For any union of data, such as that in Figure 3, an important question that we must consider is whether these data from various times, even days, can be combined and treated as a whole. This question may be rephrased to ask whether at a given plasma line frequency and altitude the plasma waves always have the same intensity. If the energy input into the plasma waves is primarily from suprathermal electrons, generated by collision processes (secondary electrons), then the waves will have nearly the same intensity. This is evident from consideration of the *Yngvesson and Perkins* [1968] linear plasma theory. The important terms are unchanged. The electron density is constant because the observed frequency is fixed. The electron temperature is constant because the energy input and loss rates are constant. The value of f_P is nearly constant because the production rate is constant and the loss rate to electrons and neutrals is constant. However, at altitudes higher than those considered here the loss rate to neutrals could be more variable.

If collisionless processes involving long-wavelength plasma waves are an important energy source for the observed plasma waves, then we may expect the intensity to depend not just on the electrons that create the ionization at the observed altitude but also on the more energetic ones that penetrate to lower altitudes. The resultant intensity could therefore, in principle, depend upon the energetic electron spectrum. However, our observations here would be less sensitive to this effect because they were made so near the peak of the E layer that there were few electrons that penetrated lower.

Therefore the data points in Figure 3 should be unique or nearly so. By turning the above arguments around to investigate the importance of collisionless processes, we learn that data are needed where the electron density profiles are the same at the observed altitude but very different at lower altitudes.

CONCLUSIONS

The plasma line portion of the incoherent scatter spectrum has been detected for the first time in the auroral E layer. These are the first detections where the suprathermal electrons that are in contact with the plasma waves definitely originate from the precipitation of energetic electrons. The altitude region where plasma lines have been measured has been lowered by about 25 km, to 98 km. The energy of the electrons that can now be investigated has been lowered considerably, to 0.55 eV. These low energies are exceedingly hard to investigate by any other technique, ground based or otherwise. In future experiments it should be feasible to lower the altitude and energy still further. Thus we have greatly extended the physical conditions under which plasma lines have been measured. Moreover, the data reflect the physical conditions and, as a result, hold the potential for providing information about the mechanism that produces the suprathermal electron distribution, the magnitude of the suprathermal flux, and the effects of electron-neutral interactions.

Acknowledgments. I gratefully acknowledge the assistance of many people in the Incoherent Scatter Group at SRI, particularly M. J. Baron, G. H. Burch, C. H. Dawson, S. D. Evitt, J. C. Hodges, J. D. Kelly, J. Petriceks, and T. S. Shaham. I would also like to acknowledge helpful discussions with F. W. Perkins and E. S. Oran. The research has been supported in part by contract DNA001-77-C-0042 from the Defense Nuclear Agency and grant ATM72-01644/A05 from the Aeronomy Section of the National Science Foundation to SRI International.

The Editor thanks L. Duncan and J. Fedder for their assistance in evaluating this paper.

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(Received March 6, 1978;
accepted June 7, 1978.)